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SOLAR WIND STREAM EVOLUTION

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Abstract Highlights of the recent progress in understanding the problem of high speed stream evolution with increasing heliocentric distance are reviewed. Crucial to this understanding are the measurements made in the inner solar system by Helios and the outer solar system by Pioneers 10 and 11. When coupled with observations at 1 AU these measurements allow a testing of current theoretical models of stream evolution.

Ever since the pioneering measurements of Mariner II (Snyder *et al.*, 1963) there has been a continued theoretical and experimental interest in the physics of the spatial (particularly the radial) evolution of high speed streams in the solar wind. The intent of this short review is to present the author's interpretation of the outstanding developments in this area of research which have occurred since the time of the 1974 Asilomar Conference.

Prior to the above-mentioned conference, virtually all of our experimental information concerning stream evolution was derived from *in situ* measurements made in the ecliptic plane between about 0.7 and 1.5 AU. Despite the limited global perspective provided by such sampling, a surprisingly large amount of knowledge was gleaned from such measurements. It was well recognized, for example, that variations in solar wind flow parameters tended to be coupled to one another, particularly near the leading edges of high speed streams. Figure 1, which shows the result of superposing 23 streams which contained abrupt interfaces (see e.g. Belcher and Davis, 1971), illustrates this coupled variation between pressure, density, flow speed, and flow direction. Such variations suggested an interpretation in terms of the radial steepening of large amplitude velocity waves. In particular, the large pressure signal which appears on the rising speed portion of a stream was thought to result from this steepening. The pressure gradient associated with this pressure signal provides a force which accelerates the low speed gas in front of the stream and decelerates the high speed gas within the stream itself. For quasi-stationary corotating streams, a pressure ridge develops nearly along the Archimedian spiral so that as the slow

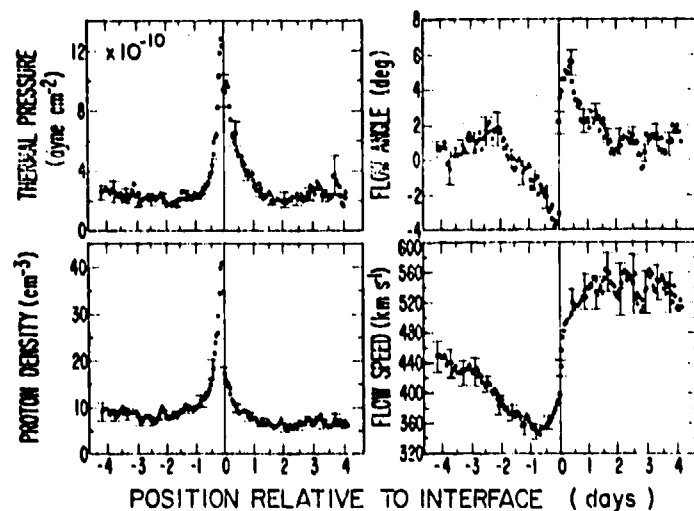


Fig. 1. The characteristic variation in pressure, density, flow speed, and flow direction observed at the leading edges of high speed streams. These are the average profiles of 23 streams which contained abrupt interfaces. From Gosling *et al.* (1978).

gas is accelerated it is deflected in the sense of corotation with the sun, and as the high speed gas is decelerated it is deflected in the opposite direction (see Figure 1). Several models of various sophistication were constructed to study stream evolution (e.g., *Carovillano and Siscoe, 1969; Hundhausen, 1973*). These models successfully mimicked the observed coupled variations in flow parameters such as shown in Figure 1, and thus provided an appealing explanation of these variations. However, at the time of the 1974 Asilomar Conference, stream steepening (or evolution) had never been detected directly; rather, it had been merely inferred from the observations and the models. Further, all of the models predicted the formation of forward reverse shock pairs on the leading edges of streams at some distance from the sun. Yet such shock pairs were rarely, if ever, actually observed between 0.7 and 1.5 AU.

In a presentation at the Asilomar Meeting of data from Pioneer 10 and 11 (both of which journeyed beyond 5 AU), *Collard and Wolfe (1974)* provided evidence that streams decay slowly in amplitude with increasing distance from the sun. Their evidence is shown in Figure 2a, which displays histograms of 100 days of Pioneer 10 and 11 speed data at two different distances from the sun. The reduced range of speed values at Pioneer 10, then at the greater heliocentric distance suggests that stream amplitudes decay by the exchange of momentum from the fast gas to the slow gas as predicted by the models. However, their presentation of time plots of the speed data (Figure 2b) provided no indication of the much-advertised shock pairs.

PIONEER 10 AND 11 SOLAR WIND DAILY SAMPLES

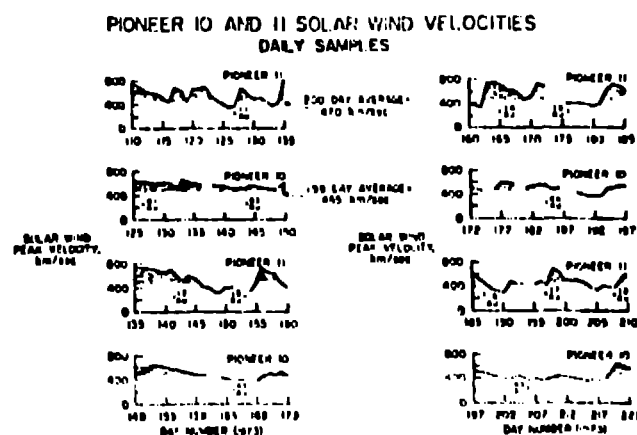
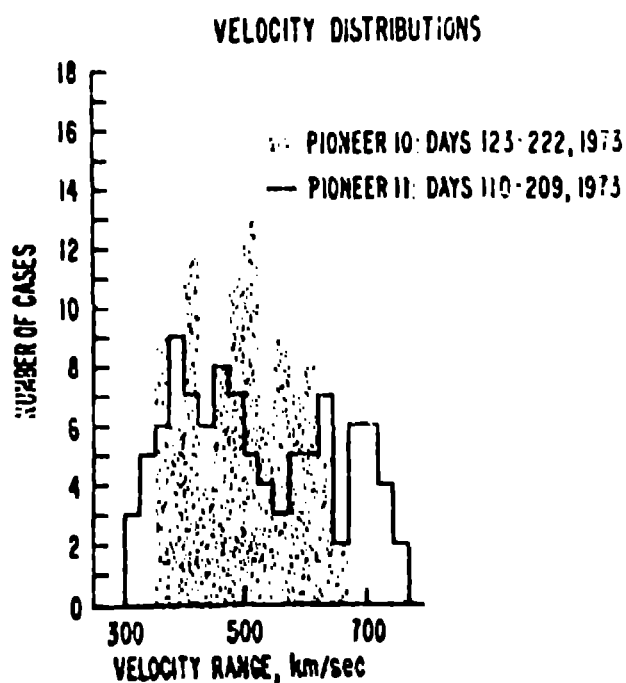


Fig. 2a. Histograms of 100 days of Pioneer 10 and 11 speed data at two different distances from the sun.
Fig. 2b. Daily samples of the solar wind speed measured by Pioneer 10 and 11. Both of these figures are from *Col-*

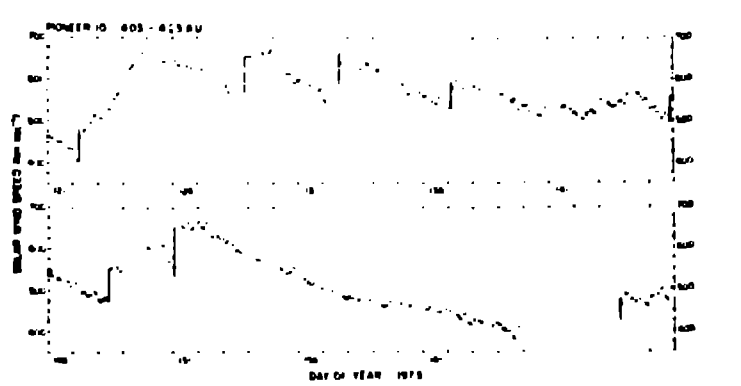


Fig. 3. Hourly samples of Pioneer 10 speed measurements between 4.03 and 4.23 AU. The vertical lines indicate abrupt jumps in speed which are shocks. From *Hundhausen and Gosling* (1976).

Later, more detailed, studies of the Pioneer 10, 11 plasma and field data revealed that the shocks did indeed exist at large distances from the sun. Hourly samples of the solar wind speed as observed by Pioneer 10 while cruising between 4.03 and 4.23 AU are shown in Figure 3. *Hundhausen and Gosling* (1976) found that the leading edges of streams beyond ~ 4 AU almost universally contained abrupt jumps in speed. They suggested that these abrupt increases were the shocks predicted by most stream models. However, these authors were unable to prove the existence of shocks because they lacked data with sufficient temporal resolution as well as information concerning density, pressure, and field strength. Conclusive proof that the shocks existed was provided by *Smith and Wolfe* (1976; 1977). An example of simultaneous speed and field magnitude measurements by Pioneer 10 at 4.3 AU is shown in Figure 4. It is apparent here that the abrupt speed jumps on the leading edge of this stream bracket a region of intensified field strength. Smith and Wolfe went on to show that abrupt changes in density

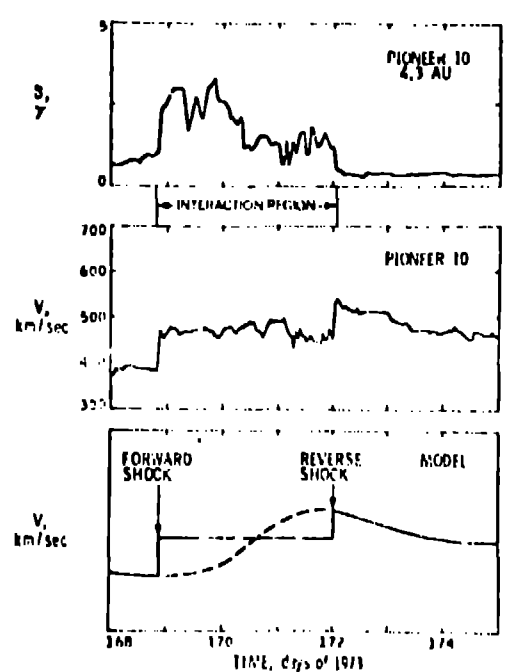


Fig. 4. Simultaneous field and speed measurements for a shock pair observed by Pioneer 10, together with a qualitative model prediction. From *Smith and Wolfe* (1976).

and temperature occur simultaneous with the speed and field changes, and that the observed changes are consistent with an interpretation in terms of shocks.

The question arises, however: 'How well do the models describe the processes of stream steepening and shock formation?' The August-September 1973 interval provided an excellent opportunity to answer this question since the sun, the earth, and Pioneer 10 were nearly coaligned at this time, with Pioneer 10 being 4.5 AU from the sun. The upper panel of Figure 5 provides a direct comparison of the speed profiles of a broad complex stream as observed near earth by IMP 7 and at 4.5 AU by Pioneer 10 during this interval. The Pioneer 10 data were shifted in time to allow for the nonaccelerated transit of the leading edge of the stream from earth to Pioneer 10. The advance of the leading edge of the stream, the overall steepened profile, and the sharp jumps in speed at the leading edge of the stream in the Pioneer 10 data are all qualitatively consistent with the predictions of the models. The bottom panel makes an explicit comparison between the profile predicted by a simple 1-dimensional gas dynamical model (Hundhausen, 1973) and that actually observed by Pioneer 10. (The IMP 7 observations of speed, density, and pressure as the stream passed 1 AU were used as the input for the calculation.) The model adequately predicts the major features of the speed profile as observed at 4.5 AU, although small differences in detail exist. It is to be expected that more sophisticated models would improve the detailed agreement. A recent study by Dryer *et al.* (1978) for a period of coalignment of Pioneer 10 and 11 and the sun and using a slightly more sophisticated model indicates that this is indeed the case. Their work shows that the models can adequately predict density and field profiles as well.

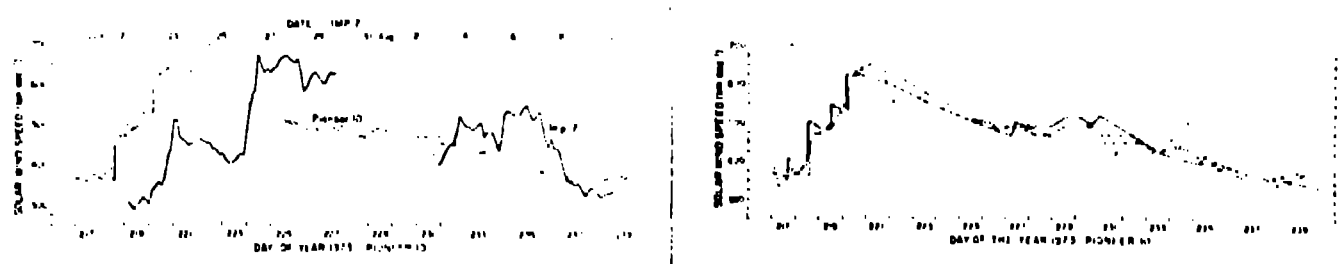


Fig. 5a. A direct comparison of the speed profiles of a complex high speed stream observed both at 1 AU (IMP 7) and at 4.5 AU (Pioneer 10).

Fig. 5b. A model prediction of the speed profile at 4.5 AU derived from the measurements at 1 AU, as compared to that actually observed. Both of these figures are from Gosling *et al.* (1976).

Figure 6 provides a comparison similar to the previous example for the stream observed on the next solar rotation when Pioneer 10 was $\sim 25^\circ$ off the sun-earth line. Again, the stream evolution between 1 and 4.65 AU is readily apparent in the data, and the model adequately predicts this evolution. Note in particular that the model predicts that the high frequency structures present on the leading edge of the stream as it passed 1 AU should be damped out by the time the stream reaches 4.65 AU; a similar fate is predicted for the low amplitude feature on the tail of the stream. Such damping is in fact observed in this example. In a more extensive theoretical study of this effect, Hundhausen and Pizzo (unpublished manuscript) have argued that the solar wind should act like a "low pass filter" in the sense that it transmits speed inhomogeneities of long wavelength much more efficiently

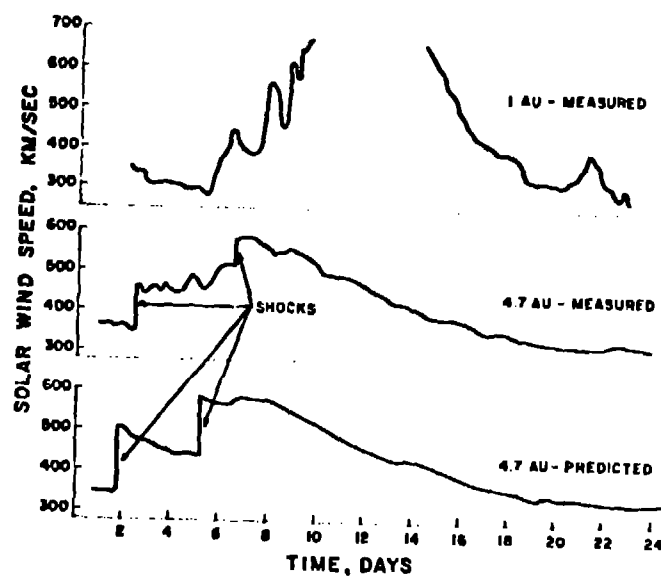


Fig. 6. A comparison of the speed profiles of a stream observed at 1 AU (IMP 7) and at 4.65 AU (Pioneer 10), together with a model's prediction of the speed profile at 4.65 AU. Adapted from *Gosling et al.* (1976).

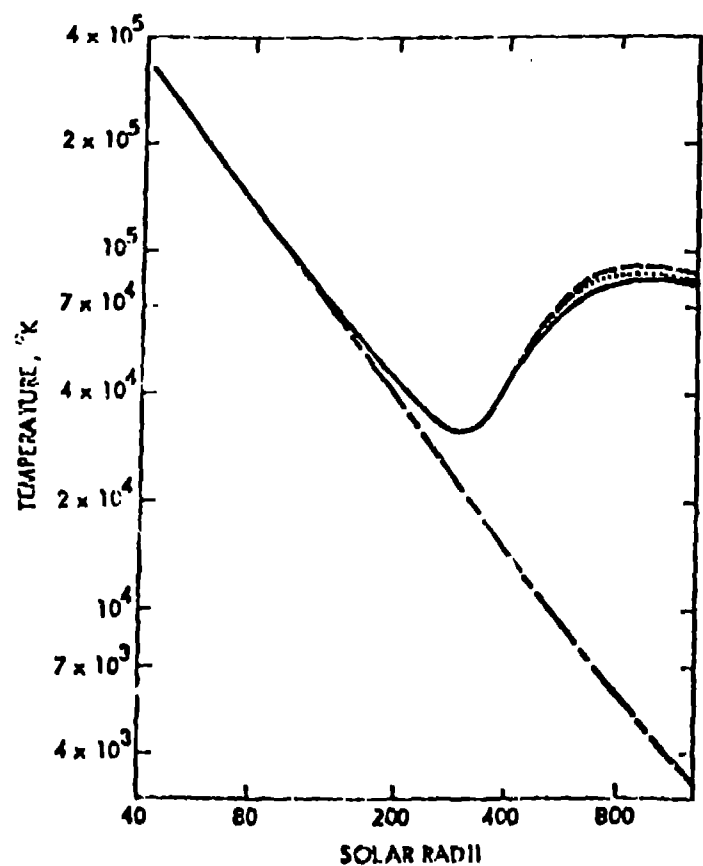


Fig. 7. A prediction of the effect of stream structure on the average radial gradient of solar wind ion temperature.

The severely altered structure of high speed streams at large heliocentric distances makes difficult the task of determining radial gradients of such quantities as density, temperature, field strength, and angular momentum which might be compared with theoretical predictions. *Goldstein and Jokipii* (1977) have used a model of stream evolution similar to those already mentioned to predict how the evolution of stream structure might affect determinations of radial gradients. Figure 7, taken from their work, illustrates how stream structure might be expected to affect the average ion temperature as a function of heliocentric distance. The long-short dashed line is the adiabatic decrease expected in the absence of stream structure or extended mechanical heating. With stream structure present, their model predicts a substantial departure from the adiabatic curve beginning at about $400 R_{\odot}$ (1.86 AU), a result of dissipative heating associated with shock formation. By assuming an inverse relation between density and velocity near the sun (see e.g. *Pizzo et al.*, 1973) Goldstein and Jokipii also predict that the average azimuthal velocity beyond $\sim 4 \text{ AU}$ may be in the direction *opposite* to solar rotation. This unexpected conclusion results because the thin high speed gas and thick low speed gas experience different accelerations at the interaction front, and components of these accelerations are directed in the azimuthal direction (see e.g. the discussion pertaining to Figure 1).

For time-stationary streams, it is solar rotation that ultimately drives the evolution of stream structure with increasing heliocentric distance. Thus we might expect stream evolution to proceed at different rates at different solar latitudes. *Suess et al.* (1975) and *Siscoe* (1976) have considered simple examples of the evolution of streams in three dimensions. Figure 8, taken from Siscoe's work, shows in three dimensions a shock surface resulting from stream evolution. For this particular example he assumed a square-wave variation of speed with longitude near the sun. The edge of the stream was aligned along a solar meridian. For such a stream the rate of streamline convergence induced by solar rotation is a maximum in the equatorial plane and zero over the poles. As a result, the shocks associated with the evolution of the stream form closest to the sun in the equatorial plane. Other shock

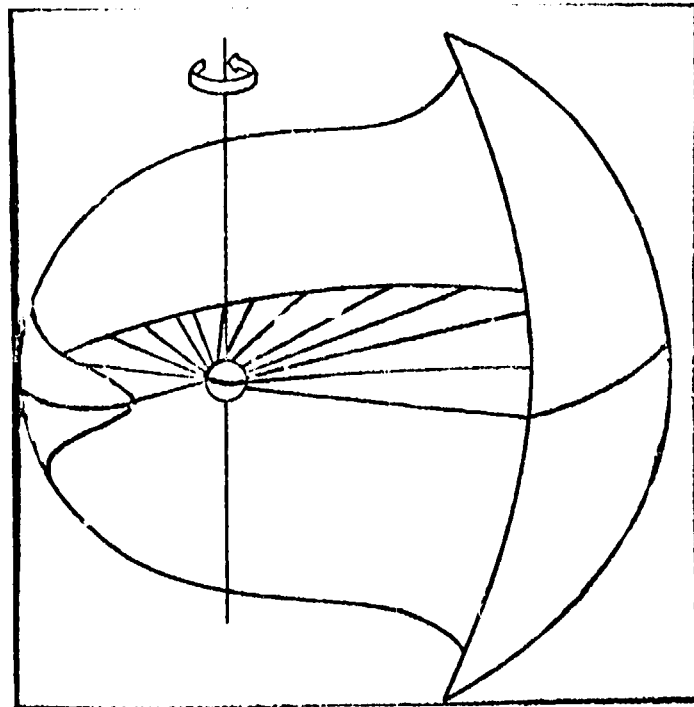


Fig. 8. A model's prediction of a single corotating shock surface in three dimensions. The location of the corotating shock is indicated by lines radiating from the sun. From *Siscoe* (1976).

surface geometries are obtained when one changes the initial boundary conditions. Nevertheless, the result of Siscoe and Suess et al. has general application: Streams whose spatial widths are nearly constant with latitude near the sun should evolve with increasing heliocentric distance at a slower rate at higher solar latitudes. Tests of this prediction should be possible with the Solar Polar Mission experiments scheduled for launch in 1983.

Until very recently, the study of the problem of stream evolution in 3 dimensions was limited to special cases such as we have just discussed. Pizzo (1977, 1978), however, has succeeded in developing a nonlinear 3-dimensional code to study stream evolution. Figures 9 and 10 illustrate the application of this code to the evolution of a simple stream for which the radial velocity alone is a function of position at the inner boundary. Since the source surface is a sphere, Pizzo has chosen to represent this 3-D stream as a contour plot projected on to a globe of radius 0.16 AU (Figure 9a). The stream rises from a uniform surrounding flow of 290 km s^{-1} to a peak of 580 km s^{-1} at the equator. The circular pattern and even spacing of the contours indicate that the radial velocity variations are symmetric about the stream core. Figure 9b shows a velocity-vector plot of the nonradial motions at 1 AU resulting from the stream steepening superposed on density contours at 1 AU. Pressure and temperature variations are identical to the density variations since the code is adiabatic. The compactation of density contours on the western edge of the stream and the wide spacing of contours on the eastern edge illustrate the familiar compression and rarefaction in density caused by stream steepening. Azimuthal and meridional motions are driven by the pressure gradients which result from the stream steepening. Maximum nonradial motions occur where the gradient is steepest. The figure helps to emphasize the flow of material away from the compression and into the rarefaction. Because the nonradial motions induced by stream evolution are small, a stream such as this does not spread much in latitude. Figure 10 illustrates this by showing the displacement of an originally uniform

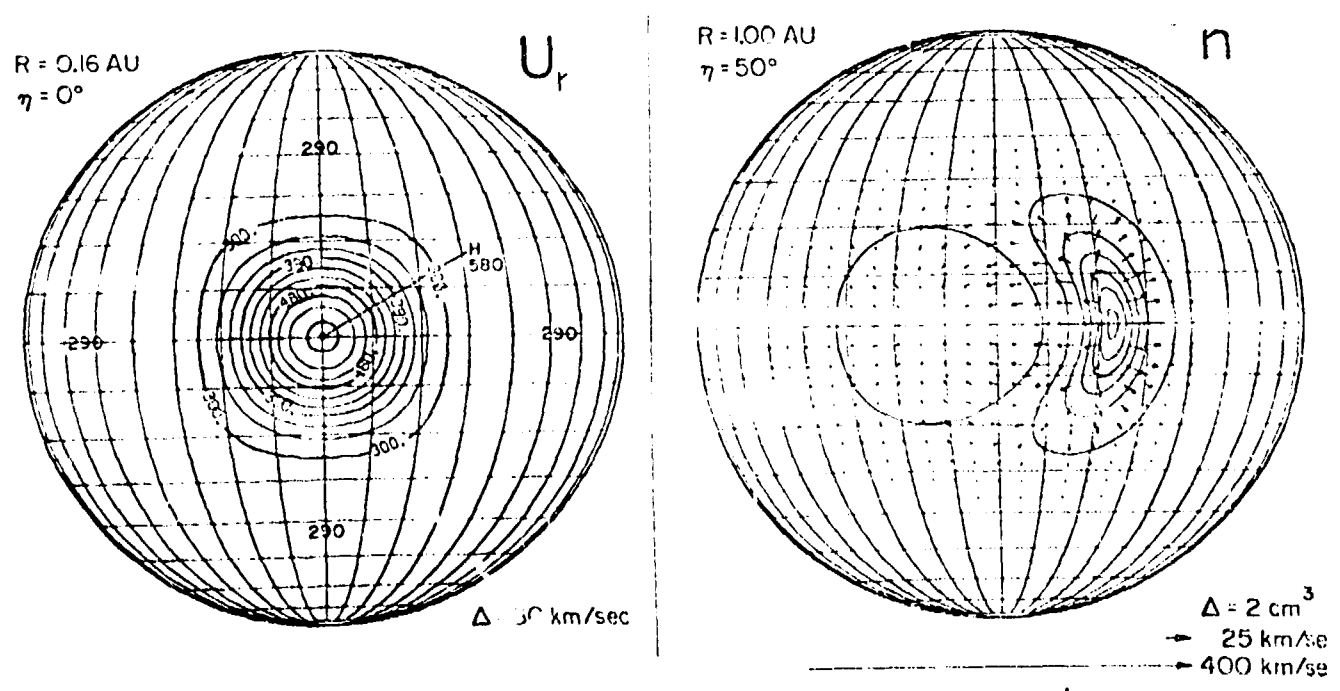


Fig. 9a. Boundary conditions for a simple 3-D solar wind stream plotted as an iso-velocity contour plot on a sphere.

Fig. 9b. A velocity-vector plot of the nonradial motions at 1 AU induced by the steepening of the stream of 9a. These nonradial motions are superposed on the density contours which result from the steepening. Both of these

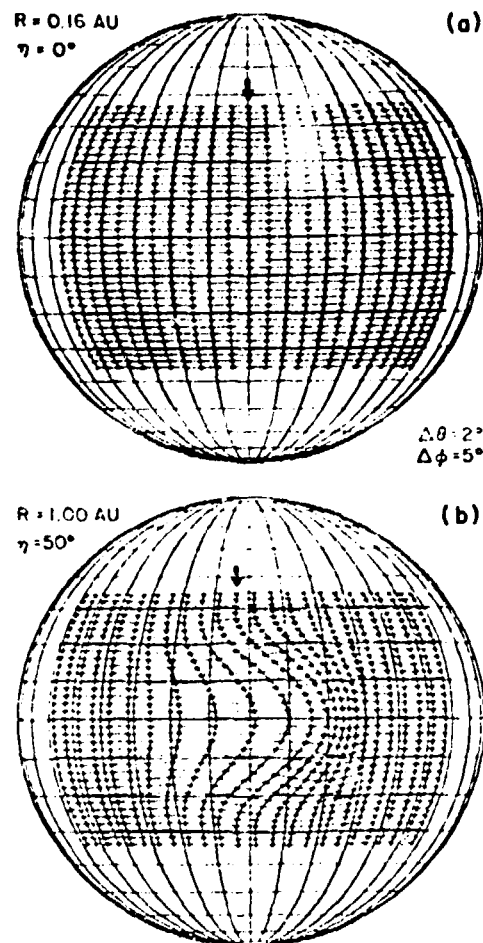


Fig. 10. The distortion by stream evolution of a uniform grid of markers placed in the stream of Fig. 9. From Pizzo (1978).

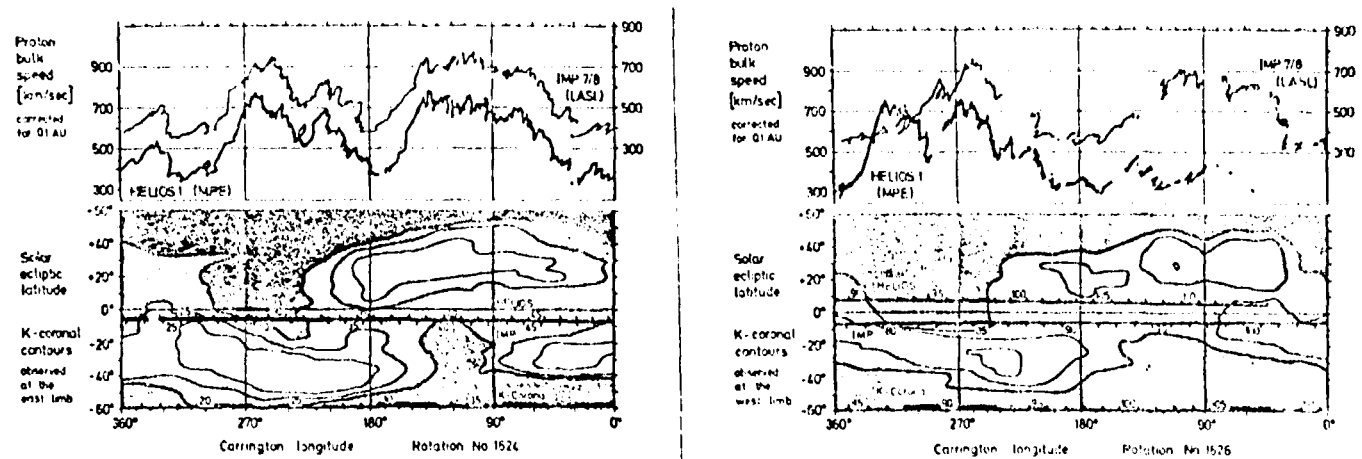


Fig. 11a. Helios and IMP solar wind speed data mapped to 0.1 AU using the constant speed approximation. The lower panel presents contours of coronal brightness at $1.5 R_{\odot}$. During this interval Helios was at approximately the same latitude as the earth-orbiting IMP satellites.

Fig. 11b. Similar to 11a but ~2 months later when Helios and the IMPs were separated by $\sim 10^\circ$ in solar latitude.

grid of markers placed in the stream flow. Pizzo concludes that streams which are sharply bounded in latitude at (say) $3R_{\odot}$ should remain relatively sharply bounded ever thereafter.

Indeed, recent observations do suggest that many streams *are* sharply bounded in latitude close to the sun. Our best evidence for this comes from the Helios observations near 0.3 AU (Schwenn *et al.*, 1978). Figure 11a shows Helios measurements of solar wind speed as a function of solar longitude just prior to perihelion passage, together with IMP 7, 8 measurements of the speed at 1 AU and contours of coronal brightness (roughly proportional to coronal electron density) at $1.5 R_{\odot}$. Both the Helios and IMP measurements have been mapped to a common radius of 0.1 AU using the constant speed approximation. The track of the two spacecraft in solar latitude and longitude is noted on the bottom panel. During this solar rotation the spacecraft were at almost identical latitudes, and both spacecraft saw essentially the same solar wind structure. It is apparent that the 2 major streams observed during this rotation originated in the 2 large coronal holes which extended from either pole of the sun down to the equatorial regions. Figure 11b illustrates a completely different degree of correlation obtained shortly after perihelion passage when the spacecraft were separated by $\sim 10^{\circ}$ in latitude. Note how Helios passed far north of the coronal hole near 90° longitude and completely missed the stream there. From these observations Schwenn *et al.* have calculated that the latitudinal gradient in speed at the edge of this stream was at least $30 \text{ km s}^{-1} \text{ deg}^{-1}$, and may have been as large as $100 \text{ km s}^{-1} \text{ deg}^{-1}$. One swallow does not make a spring, and one sharp edged stream does not establish a general rule. Nevertheless, these observations are intriguing, and work by others (e.g. Rhodes and Smith, 1976) supports the concept of streams sharply bounded in latitude at a variety of distances from the sun.

Then, too, there exist a number of diverse observations which suggest that many streams are also sharply bounded in longitude close to the sun. For example, Rosenbauer *et al.* (1976) found that the leading (or westward) edge of some streams observed inside of 0.5 AU were steeper than typical stream edges at 1 AU. Nolte *et al.* (1970)

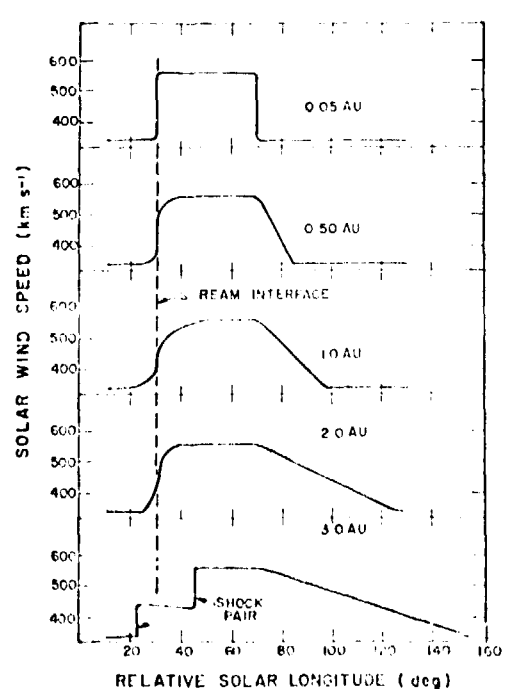


Fig. 12. A qualitative model of the evolution of a highly idealized stream with increasing distance from the sun. From Gaslina *et al.* (1978)

and others have mapped stream profiles observed at 1 AU back to the corona (by assuming that the speed is constant at all heliocentric distances) and have inferred that the trailing (or eastward) edges of many streams appear to originate from a single longitude. And, *Gosling et al.* (1978) suggest that abrupt stream interfaces at 1 AU are caused ultimately by large velocity shears in longitude close to the sun.

If large velocity gradients exist on the edges of streams close to the sun as the observations suggest, then the interplanetary magnetic field must play a more important role in stream evolution inside of 1 AU than heretofore recognized. (Our discussion relative to Figure 5 and 6 indicates that the field plays only a minor role in stream evolution beyond 1 AU.) In particular, the large magnetoacoustic speed close to the sun allows a steep-edged stream to damp initially without the formation of shocks. Figure 12 provides a qualitative illustration of how a stream bounded by large velocity shears might evolve with increasing heliocentric distance in the ecliptic plane. At the leading edge of the stream (the left-hand edge in the figure) a continual competition occurs between the tendency for the stream to steepen (i.e. for stream lines to converge) and for the pressure ridge induced by the convergence to expand outward and limit the steepening. Initially, because the magnetoacoustic speed is high, the latter process dominates and the leading edge of our idealized stream flattens with increasing distance from the sun. Eventually, however, the streamlines converge more rapidly than the pressure ridge can expand outward because both the convergence increases and the magnetoacoustic speed decreases. Thus this idealized stream is steeper both at 0.5 and at 2.0 AU than it is at 1 AU. The continual transfer of momentum across the interface causes a gradual reduction with distance of the shear which occurs there. At very large distances the shear is removed and the stream is shocked.

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